

A Comprehensive Review on Performance Evaluation and Modelling of Wastewater Treatment Plants Using GPS-X

MOHAMMAD ALJAMHAWI

eng-mohammad97@hotmail.com

Bashar Ammary

Kamel Alzboon

Husam Mahasneh

Systematic Review

Keywords: GPS-X Modelling, Wastewater Treatment, Process Optimization, Energy Efficiency, Pollutant Removal

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11180555/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Wastewater treatment is a key element in environmental conservation, ensuring conformity to regulatory standards and efficient utilization of water resources. Computer modeling programs such as GPS-X have significantly enhanced wastewater treatment plant (WWTP) performance evaluation by simulating biological, chemical, and physical processes. The article provides a comprehensive review of the use of GPS-X with a focus on pollutant removal efficiency, energy consumption, cost-effectiveness, and process optimization. The research employs a systematic literature review approach, reviewing peer-reviewed literature accessible between 2002 and 2025. The data collection centered on biological treatment, nutrient removal (BNR) studies, membrane bioreactors (MBRs), sequencing batch reactors (SBRs), and sludge management practices. The results reflect significant variability in pollutant removal efficiencies, ranging from 65.8% in the case of microplastics to 94.2% for total suspended solids (TSS), and high energy consumption values ranging between 3.1 and 5.2 kWh/m³, depending on the intensity of aeration and treatment complexity. Cost estimates point towards operational costs ranging between \$0.10 and \$0.18 per cubic meter, with implications of trade-offs between economic viability and treatment effectiveness. While GPS-X is able to simulate treatment operations with great accuracy, emulated and actual performance are not the same, requiring advanced calibration procedures, real-time data fusion, and machine learning-tuned corrections. The research also explores the use of GPS-X to simulate future contaminants of concern and evaluate the climate resilience of WWTPs. Finally, although GPS-X is an optimal model for the optimisation of wastewater treatment plants, its predictive capability could be enhanced through better calibration strategies, dynamic models, and AI-based analytics to enable sustainable wastewater management.

1. Introduction

Water pollution and wastewater management pose the biggest issues in today's world, due to heightened industrialization, urbanization, and population growth. Wastewater treatment plants (WWTPs) are major sources of environmental contamination through the treatment of wastewater before it is discharged into natural watercourses. Such operations of treatment plants are influenced by numerous environmental parameters regulating their performance, economic feasibility, and adherence to increasingly stringent environmental protection requirements (Abdul-Kareem & Al-Baidhani, 2024; Zanolli, 2024; Mannina et al., 2025). The availability of computational modeling software enabled the implementation of an unparalleled methodology to characterise and optimise wastewater treatment processes to inform decision-making on the design and operation phase of a treatment plant. Of these technologies, GPS-X, a dynamic simulation computer program for wastewater treatment, has become a leading platform for simulating treatment plant performance under changing operating conditions. By providing detailed explanations of biological, chemical, and physical processes, GPS-X enhances the capability for treatment efficacy to be measured and system performance to be optimized (Zwain et al., 2024; Emaminejad, 2024; Stenberg, 2024).

Over the past twenty years, a lot of intense research has focused on the simulation of wastewater treatment plants, with expanding interest in what GPS-X is capable of doing and what purposes it serves. The program is now very prevalent for the assessment of treatment performance, nutrient removal capacities, sludge management, and energy consumption (Odeibat et al., 2024; Aliyu et al., 2025; Sergienko, 2024). It has worked well in mimicking treatment processes such as steady-state activated sludge processes, membrane bioreactors (MBRs), sequencing batch reactors (SBRs), and anaerobic digestion processes (Salman et al., 2024; Stenberg et al., 2025; Le, 2024). In terms of how much it can be used in wider and more accurate situations, a difference between actual and simulated plant performance is an indicator of the model's calibration and validation level. GPS-X predictability and reliability are warranted in the context of its use on several treatment modes in non-homogeneous influent conditions and uncertain operation (Sun et al., 2025; Mannina et al., 2025; Zwain et al., 2024).

The increasing emphasis on sustainability and process optimization has also further encouraged the application of modelling techniques in wastewater treatment research. Since WWTPs are subjected to budgetary constraints, regulatory requirements, and shifting environmental considerations, the necessity for effective simulation tools to maximize process performance has increased (Aliyu et al., 2025; Sheik et al., 2024). GPS-X has enabled scenario calculations, enabling researchers and engineers to compare system modifications, optimize operating conditions, and examine cost-effective options for increased treatment performance (Mannina et al., 2025; Zwain et al., 2024). The degree to which GPS-X models closely resemble real-world reality, though, depends on input data accuracy, kinetic parameter tuning, and consideration of site-dependent factors. Overcoming such limitations is a priority area in creating real-world applications of wastewater treatment model development (Emaminejad, 2024; Stenberg, 2024).

Aside from conventional performance monitoring, GPS-X has progressively been applied to studies of innovative pollutant behavior and fate within wastewater treatment systems. Pharmaceuticals, microplastics, and industrial pollutants are examples of problems of vital environmental and public health relevance but whose effluent removal performance from conventional schemes is unpredictable (Salman et al., 2024; Stenberg et al., 2025; Sun et al., 2025). GPS-X model-based simulation research has added to the understanding of such pollutants' motion and transformation and guided future prospective upgrading of treatment technologies (Aliyu et al., 2025; Odeibat et al., 2024). Such predictive power nonetheless still depends on laboratory-based studies and long-term monitoring data. The capacity of GPS-X to simulate the interactions between emerging pollutants and treatment processes continues to be a research interest (Mannina et al., 2025; Zwain et al., 2024).

The capacity of wastewater treatment plants to withstand the climate change scenario has also been of interest, where GPS-X was utilized to model the impacts of rising temperatures, weather occurrences, and altering precipitation trends on the treatment process (Le, 2024; Sun et al., 2025; Sheik et al., 2024). Simulation-based assessment has shed light on probable weaknesses of treatment systems and adaptive management strategy development (Abdul-Kareem & Al-Baidhani, 2024; Zanolli, 2024). Despite all such developments, integration of real-time data monitoring, uncertainty analysis, and emerging

computational approaches such as machine learning remains a challenge (Stenberg et al., 2025; Salman et al., 2024). The ability of GPS-X to adapt to climate-resilient wastewater treatment practices is an area that needs further exploration, particularly within the context of shifting environmental realities and dynamic regulatory landscapes (Emaminejad, 2024; Odeibat et al., 2024).

This study reports a comprehensive review of the literature on applications, advantages, and constraints of GPS-X for simulation and performance evaluation of wastewater treatment plants. This study emphasizes the critical assessment of the application of GPS-X for evaluation of treatment efficiency, optimization of operating strategy, and solution of prominent issues in wastewater. This research identifies research gap areas based on integration of current studies and consideration of the accuracy and validity of GPS-X models. It demands the enhancement of simulation methods towards more relevant and precise outcomes. This study also investigates the implications of GPS-X modelling in the management of emerging pollutants and climate resilience, directing towards its capability to guide sustainable wastewater treatment practices. Through a literature review of the methodology, the study situates GPS-X within the broad context of wastewater treatment studies and thus confirms its relevance to the formulation of scientific and engineering solutions for water resource management.

2. Research Methodology

2.1 Research Design

This study uses a systematic literature review method to explore the applications, advantages, and drawbacks of GPS-X in wastewater treatment plant (WWTP) performance assessment and modeling. The review synthesizes up-to-date research evidence, critically evaluates modelling accuracy and dependability, and establishes gaps in the existing research in the field. Both qualitative and quantitative data extraction methods were applied to ensure comprehensive evaluation of relevant studies.

2.2 Data Collection and Sources

Relevant research papers were obtained by systematically searching peer-reviewed journal articles, conference papers, theses, and technical reports from prominent academic databases like Scopus, Web of Science, Google Scholar, and ScienceDirect. Relevant keywords were employed in the search strategy, such as GPS-X modelling, operation of wastewater treatment plants, process optimization, nutrient removal modelling, emerging contaminants in WWTPs, and wastewater treatment's adaptability to climate change. In order to reflect the evolution of research in this field, articles between 2002 and 2025 were considered. The database search was carried out between March and May 2025, with the reference list finalized in June 2025 prior to submission.

Figure 1 presents the frequency plot of the top 10 most significant keywords of the research study conducted on GPS-X modeling in wastewater treatment plants (WWTPs). These are the primary themes of thematic focus, including process optimization, performance evaluation, nutrient removal, computational modeling, and environmentally friendly water management. The frequency values

between 0 and 40 indicate relative concentrations of the topic themes in the research study. The visualization highlights the significance of GPS-X as an optimization tool at the computer level for wastewater treatment, model parameter estimation, and future contaminant evaluation.

2.3 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were developed in order to identify suitable and good-quality studies to include in the scope of this review. Inclusion was determined based on the grounds that the studies were employing GPS-X for modelling of wastewater treatment plants with performance assessment, process optimisation, removal of nutrients, or modelling of emerging contaminants as the area of interest. Only peer-reviewed journal papers, conference publications, and technical reports were acceptable to confirm the reliability and validity of the sources. In addition, journals from 2002 to 2025 were selected to track progress in wastewater treatment modelling over the years.

Conversely, studies conducted without the utilization of GPS-X as a primary modelling tool were ruled out because this review seeks to analyze its specific applications. Studies that were not very methodologically transparent or did not have sufficient data on the applications of GPS-X were ruled out to guarantee the validity of the findings. Furthermore, studies before 2002 or not directly relevant to wastewater treatment performance evaluation were not included as they might not reflect the current advancements in modelling techniques. Finally, non-English documents were not included to prevent language constraints from affecting the technical content and conclusions being read accurately.

2.4 Thematic Analysis

Thematic analysis conformed to Braun and Clarke's (2006) six-step approach to methodically identify patterns and draw key conclusions from the reviewed literature on GPS-X applications for wastewater treatment plant (WWTP) modeling:

1. Familiarization with Data: Articles were thoroughly read several times to identify common themes about wastewater treatment modeling, process optimization, pollutant removal, and efficiency in operations.
2. First code generation: Essential features were coded under themes such as biological and chemical treatment processes, energy consumption, model calibration, and nutrient removal efficiency.
3. Theme identification: Codes were given to broad themes, including simulation quality, computational challenges, cost-benefit trade-offs, and process control innovation.
4. Theme refinement: Themes were rendered consistent and coherent to prevent duplication or redundancy. This was also accompanied by cross-validation of trends that were arising from different case studies.

5. Identification and Labeling Themes: Clearly defined sub-themes, such as the role of GPS-X in optimizing aeration efficiency, impact on removal of emerging contaminants, and limitations in predicting real treatment dynamics, were identified.
6. Formulation of the Final Report: Synthesized themes were analyzed and connected to available literature, illustrating their importance in improving wastewater treatment modeling accuracy, optimizing operation sustainability, and overcoming difficulties related to GPS-X calibration and validation.

2.5 Data Extraction and Analysis

A structured data extraction model was developed to systematically arrange and synthesize selected literature. The studies were thoroughly reviewed, and critical parameters were recorded to ensure critical synthesis of research evidence. The extracted data included citation and source information in APA 7 referencing style to ensure consistency of documentation. The primary research goals of each included study were identified, such as subjects that involve assessment of treatment effectiveness, optimization of process design, modeling of new pollutants, and climate resilience.

In addition, the research methodology of each study was examined, classifying studies based on whether they employed experimental verification, computer simulation, sensitivity analysis, or uncertainty assessment. The most prominent findings and contributions were documented, highlighting results pertinent to treatment efficiency, energy effectiveness, sludge reduction, and regulatory compliance. Moreover, issues and limitations with respect to the modelling process were noted, namely model accuracy, availability of data, and field use. This structured approach facilitated critical review of relevant research to allow robust evaluation of the uses of GPS-X for wastewater treatment.

2.6 Critical Appraisal and Quality Assessment

A rigorous quality evaluation process was adhered to in order to provide credibility and reliability of studies incorporated. The suitability of each study for GPS-X modeling of wastewater treatment was carefully assessed, and only those most relevant studies that made significant contributions to the topic were incorporated. Methodological soundness was facilitated by assessing the calibration methodology incorporated in the studies, validation strategies, and scenario analysis. These factors were instrumental in defining the simulation models' resilience and applicability in real-life wastewater treatment operations.

Aside from that, data reporting also was of concern, and that was how studies reported input parameters, assumptions, and modelling constraints. This was to ensure that the studies selected were adequate enough to reproduce and validate. Statistical robustness was also considered on the basis of adherence to proper modelling practice and application of appropriate data analysis techniques to deliver robust reliability of results. All the studies were formally tested against such standards before inclusion in this review, which ensures that the analysis in this study is based on well-documented and high-standard research.

3. Result

3.1 Pollutant Removal Efficiency in GPS-X Simulations

The utility of GPS-X as an optimization simulation software for optimizing the pollutant removal efficiencies in wastewater treatment plants has been extensively reviewed in the literature. GPS-X is a collection of software tools supplied by Hydromantis. GPS-X is an advanced computer software that brings together different mathematical models for treatment process simulation and optimization. Its application is to all types of wastewater treatment plants, showing its ability to optimize removal efficiencies for parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium (NH₄), phosphate (PO₄), and total suspended solids (TSS). Its frequent application is in the process of phosphorus removal denitrifying where GPS-X has been shown able to produce maximum removal efficiencies through parameter optimization. For instance, phosphorus removal efficiency in Anaerobic-Anoxic-Oxic (A²/O) processes has been reported to be extremely sensitive to reflux ratio and also to solid retention times (Ai et al., 2011). GPS-X, however, has been exceptional in simulating biological nutrient removal based on well-documented models such as ASM1 and ASM3, with extensive application in organic carbon degradation and nitrogen removal (Lei et al., 2022; Arif et al., 2018).

The usability of GPS-X is also improved through evidence that confirms its predictability in full-scale wastewater treatment plants. Simulation of the Kerbala wastewater treatment plant, for example, validated the software's reliability to predict pollutant removal performance if the plant is operated under real operating conditions (Salman et al., 2024). Additionally, the inclusion of response surface methodology (RSM) in GPS-X has enhanced nitrogen removal processes, reflecting the machinery's ability to accommodate challenging treatment conditions (Cao et al., 2021).

Ease of use and optimal calibration possibilities are also responsible for its use in research and industrial practice (Moghaddam & Pirali, 2021; Abbasi et al., 2021). GPS-X is thus now a sophisticated computer program for wastewater treatment design via process control, optimization, and performance monitoring, and a broad spectrum of treatment technologies (Hellal & Abou-Elala, 2021).

In addition to the traditional treatment operations, GPS-X has also been used to simulate emerging treatment technologies such as membrane bioreactors (MBRs) and new bioreactor designs. In research, it has been set up to simulate pollutant behavior under different treatment design configurations with the objective of providing information concerning pollutant removal as well as the degradation process (Vicentín et al., 2019). Through pollutant fate and treatment effectiveness evaluation, GPS-X can facilitate more efficient and sustainable wastewater treatment systems to be adopted. With ever-tightening environmental regulations making the need for sophisticated tools like GPS-X a daily concern of growing necessity, it is now an essential tool for wastewater management and technology development.

Table 1 gives an integrated overview of the application of GPS-X to wastewater treatment across core areas including targets for pollutant removal, modeling strategy, strategies for optimization, field

application, advanced treatment technologies, and software scope. Corresponding supporting research for every area is included to highlight the scope of the application of GPS-X towards simulating wastewater treatment.

Table 1
Summary of Pollutant Removal Efficiency in GPS-X Simulations

Aspect	Description	Key References
Pollutant Removal Targets	GPS-X simulates the removal of key pollutants such as BOD, COD, NH4, PO4, and TSS, enhancing treatment efficiency.	Ai et al. (2011), Salman et al. (2024), Vicentín et al. (2019)
Key Modelling Approaches	Mathematical models such as ASM1 and ASM3 are integrated into GPS-X to simulate biological nutrient removal and organic carbon degradation.	Lei et al. (2022), Arif et al. (2018)
Process Optimization Strategies	Optimization of solid retention time and reflux ratios has been shown to improve phosphorus and nitrogen removal efficiency.	Ai et al. (2011), Cao et al. (2021)
Real-World Applications	GPS-X has been applied in full-scale treatment plants, including the Kerbala WWTP, validating its predictive capabilities in real operational conditions.	Salman et al. (2024), Moghaddam & Pirali (2021), Abbasi et al. (2021)
Advanced Treatment Technologies	GPS-X has been employed in advanced wastewater treatment technologies, including membrane bioreactors (MBRs) and enhanced bioreactor setups.	Vicentín et al. (2019), Hellal & Abou-Elela (2021)
Software Capabilities	The software provides a user-friendly interface, robust calibration tools, and integration with response surface methodology (RSM) to optimize nitrogen removal.	Cao et al. (2021), Moghaddam & Pirali (2021), Abbasi et al. (2021)

3.2 Energy Consumption and Cost Analysis of Treatment Processes

Estimation of energy usage and operating cost in wastewater treatment is becoming a point of emphasis owing to increasing environmental and sustainability needs. WWTPs are power-hungry plants, and aeration processes contribute to a major percentage of total energy demand. Oxygen demand for microbial respiration, particularly in BNR processes, is responsible for most of the operating cost (Żyłka et al., 2020). Studies have shown that energy use can contribute up to 50% of the overall operational cost, especially sludge handling and disposal in municipal wastewater treatment, which has economic effects on wastewater treatment plants (ÇEVİK, 2023). Utilization of GPS-X model simulations has facilitated large amounts of data pertaining to energy demand of various treatment configurations for enabling determination of aeration efficiency, oxygen transfer rates, and energy-saving capacity through optimization of operating strategies.

Other optimization strategies have been explored to make up for the enormous energy expenses and related energy consumption, e.g., demand management strategies, which regulate treatment activities as a function of electricity price variability to prevent peak-load consumption (Hasan et al., 2020). Novel electrochemical treatment technologies have also been shown to be cost-efficient, though with significant initial capital investment, and there are subsequent long-term cost savings from energy (Nath, 2024). Scenario analysis of GPS-X simulation facilitates the execution of different modifications in processes such as sludge retention time, aeration rate, and dosing regimens, leading to energy consumption savings. Further, such procedures for resource recovery as anaerobic digestion and co-combustion of sewage sludge facilitate the supply of energy in the form of biogas, reducing reliance on external electricity and lowering operating costs (ÇEVİK, 2023; Nourin et al., 2020).

The economic efficiency of wastewater treatment processes goes beyond the direct usage of energy and encompasses complete costing systems that quantify lifecycle costs, pollutant abatement efficiency, and long-term viability (Valero et al., 2021; Zhang & Liu, 2019). GPS-X simulations offer an arena for multi-criteria comparison, balancing cost, energy savings, and environmental trade-offs in design (Jiang et al., 2018; Ling et al., 2021). Literature indicates that achieving the perfect balance between economic sustainability and environmental health continues to be a difficult task, and holistic decision-making strategies to WWTPs are critical. Through the integration of economic analysis with optimization, GPS-X is one of the top performers in cost-effective and energy-efficient wastewater treatment technologies towards building more resilient and sustainable water management systems (Jiang et al., 2018; Nath, 2024).

Table 2 displays a table of organized details regarding energy utilization and cost calculations of wastewater plants with a unique focus on GPS-X simulations. It identifies major aspects like the requirement of energy in treatment, optimization, technique for resource recovery, and viability on an economic level. Provided references support discussions related to sustainable and cost-cutting wastewater treatment mechanisms.

Table 2
Energy Consumption and Cost Analysis in Wastewater Treatment Processes.

Aspect	Description	Key References
Energy Demand in WWTPs	Aeration and biological treatment processes constitute a significant portion of energy use, with costs comprising up to 50% of total operational expenditures.	Żyłka et al. (2020), ÇEVİK (2023)
Optimization Strategies	Demand management strategies and aeration process modifications reduce energy costs by regulating operations based on electricity pricing.	Hasan et al. (2020), Nath (2024)
Resource Recovery Techniques	Techniques such as anaerobic digestion and co-combustion of sewage sludge facilitate biogas energy recovery, reducing external power dependency.	ÇEVİK (2023), Nourin et al. (2020)
Cost-Effective Treatment Methods	Electrochemical treatment technologies, despite high capital costs, offer long-term energy savings and cost efficiency in wastewater treatment.	Nath (2024)
Economic Feasibility & Sustainability	Lifecycle cost analysis and GPS-X modelling enable a balance between cost efficiency and environmental impact in WWTPs.	Valero et al. (2021), Zhang & Liu (2019), Jiang et al. (2018), Ling et al. (2021)

3.3 Accuracy and Calibration of GPS-X Modelling

GPS-X modelling accuracy and calibration are critical in estimating the reliability of wastewater treatment simulation. As a robust simulation computer program, GPS-X is extensively used to simulate wastewater treatment processes and enhance the efficiency of operations. However, the accuracy of the simulation is comparative to high-calibration and validation processes that align model prediction with real treatment plant performance (Moghaddam & Pirali, 2021). Calibration encompasses the calibration of critical model parameters to minimize simulated and observed data differences aimed at such that the predictive values reflect real wastewater treatment dynamics to a high degree of accuracy. Effective calibration procedures make it possible for GPS-X to deal with complexity in treatment scenarios, for example, influent parameter variability, aerating efficiency, and pollutant removal rates, to add credibility to engineering applications (Moghaddam & Pirali, 2021).

High-precision calibration is a crucial aspect of model accuracy, particularly in dynamic wastewater treatment processes. Calibration methods in GPS-X enable predictive accuracy by minimizing statistical errors such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and coefficient of determination (R^2), consistent with good-modelling-practice guidelines for activated sludge models (Rieger et al., 2012). GPS-X has been used successfully to simulate hybrid biofilm reactor operation, demonstrating the importance of calibrating models against retention time distribution and respirometric test data to achieve optimum simulation outcomes (Zeng et al., 2014).

In addition to calibration technique, model structure and unit-process configuration are basic determinants of simulation precision. Studies of full-scale plants confirm that model accuracy depends not only on parameter calibration but also on influent variability, treatment plant design, and the availability of monitoring data against which the model can be checked (Al-Sayed et al., 2023; Moghaddam & Pirali, 2021). Effective wastewater treatment modelling therefore requires ongoing calibration assessment, appropriate statistical analysis, and adaptive parameter tuning. With these steps in place, GPS-X remains an efficient tool for predicting wastewater treatment plant performance in support of sustainable water resource management (Moghaddam & Pirali, 2021).

Table 3 illustrates an organized summary of accuracy and calibration approaches in GPS-X modelling with emphasis on some important areas such as calibration methods, statistical validation parameters, applications in the real world, and problems in integrating data. The references are toward highlighting the importance of precision correction, real-world synchronization of data, and minimization methods for error in rendering valid wastewater treatment simulations.

Table 3
Accuracy and Calibration of GPS-X Modelling

Aspect	Description	Key References
Calibration Techniques	Adjusting model parameters to minimize discrepancies between simulated and observed wastewater treatment data.	Moghaddam & Pirali (2021)
Statistical Validation Metrics	Accuracy assessment using Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2) to measure predictive reliability and model performance.	Yeh et al. (2008), Zeng et al. (2014)
Real-World Application of GPS-X	GPS-X has been successfully used in hybrid biofilm reactor simulations, demonstrating the importance of precision calibration.	Zeng et al. (2014)
Optimizing Modelling Performance	Continuous calibration and validation techniques improve GPS-X's application in wastewater treatment process optimization.	Moghaddam & Pirali (2021)

3.4 Limitations and Challenges in GPS-X-Based Modelling

Even though GPS-X possesses great ability to simulate wastewater treatment plant (WWTP) performances, there are limitations that act as barriers in the application of GPS-X in real applications, particularly the calibration of the model, dependency on data, and computational complexities. The most important barrier to modeling through GPS-X is calibration and validation difficulties. Calibration is a multi-step process requiring large volumes of data and large empirical observations, which are not always readily available and cannot be easily used efficiently (Moghaddam & Pirali, 2021). Process complexity in wastewater treatment leads to model over simplification, reducing prediction accuracy. Besides that, studies indicate the difficulty of obtaining model complexity with a perspective of keeping computational efficiency because less complex models would not be capable of explaining treatment

variables' intricate inter dependencies and hence resulting in simulated vs. actual performance discrepancies (Shaw et al., 2011; Zeng et al., 2014).

Another critical issue is the reliability of the input data used to build and run GPS-X models. Influent characterisation, sensor calibration, and the frequency of grab or composite sampling all affect the accuracy of the fractions and kinetic parameters supplied to the model, and gaps or inconsistencies in operational data can propagate directly into simulation error (Moghaddam & Pirali, 2021). Such difficulties underscore the need for more effective data-collection protocols, particularly in dynamic treatment systems where influent conditions change rapidly. GPS-X, within WWTP deployment, does not include built-in real-time data assimilation capabilities, which by implication limits its use for adaptive process optimization and control in current practice.

Besides data dependability and range of calibration, interpretability is also an issue with GPS-based simulation advanced models. Empirical evidence from machine learning and artificial intelligence sets out that simulations by neural network models that integrate GPS data will not be transparent and meaningful interpretations are not achievable with simulation outcomes (Thompson et al., 2023). This issue is particularly critical to GPS-X, whereby the lack of unequivocal cause-and-effect linkages among model predictions may limit its utility for real-world practical wastewater treatment decision-making. Although GPS-X remains a powerful simulation vehicle, it is an issue that necessitates continuous innovation in modelling approach, the capacity to design systems that are better comprehended, and enhanced real-time data assimilation protocols in an effort to harness GPS technology to its utmost capability for environmental and infrastructure modelling (Moghaddam & Pirali, 2021).

Table 4 is an illustration of most important obstacles or hurdles to WWTP modeling per GPS-X. It illustrates basic concerns of concerns in calibration problems, limits on data reliability, computational complexity issues, and shortcomings in model interpretability. Given references are right to comment about their overcoming using improved methodology and technology.

Table 4
Limitations and Challenges in GPS-X-Based Modelling

Aspect	Description	Key References
Calibration Challenges	Accurate model calibration requires large empirical datasets and complex validation processes, which can lead to oversimplifications and reduced accuracy.	Moghaddam & Pirali (2021); Zeng et al. (2014)
Computational Complexity	Balancing model sophistication with computational efficiency is challenging, as highly detailed models demand significant processing power.	Shaw et al. (2011)
Data Reliability Issues	Influent and operational data used to build GPS-X models may suffer from measurement error, incomplete characterisation, and limited sampling frequency, affecting model precision.	Moghaddam & Pirali (2021)
Lack of Real-Time Data Integration	GPS-X lacks built-in real-time data assimilation capabilities, limiting its potential for adaptive process control and performance optimization.	Moghaddam & Pirali (2021)
Interpretability of Model Outputs	Complex modelling frameworks, particularly those incorporating AI techniques, may suffer from a lack of transparency, reducing their practical applicability.	Thompson et al. (2023)
Challenges in Environmental Applications	The difficulty of integrating GPS-X into dynamic environmental systems requires enhanced methodologies for better adaptability and performance.	Moghaddam & Pirali (2021)

3.5 Comparative Analysis of Pollutant Removal Efficiency, Energy Consumption, and Cost Performance in GPS-X Simulations

Quantitative evaluation of wastewater treatment processes depends mainly on aspects such as the efficiency of pollutant removal, energy consumption, model performance, and operating cost. GPS-X, as an advanced simulation package, provides a generic framework for simulating these parameters under varying treatment conditions. An understanding of the trade-offs among treatment efficiency, energy needs, and economics helps in optimizing WWTP operation. A comparative comparison of some selected studies based upon GPS-X simulation gives elementary estimates of variability of treatment performance as well as the determinants of simulation accuracy.

Table 5 data show the heterogeneity of pollutant removal efficiency, energy requirement, and cost-efficiency of different GPS-X modeled wastewater treatment experiments. The highest removal of pollutants was reported for total suspended solids (TSS) at 94.2% (Salman et al., 2024), while the lowest removal rate was reported for emerging contaminants such as microplastics (65.8%) and pharmaceuticals (72.4%) (Odeibat et al., 2024). This discrepancy reflects the challenge of removing the new pollutants and the potential of other processes to increase the removal efficiency of the conventional processes.

The energy consumption levels ranged from 3.1 to 5.2 kWh/m³, and Odeibat et al. (2024) used the most energy due to added treatment complexity by the new pollutants. The lowest consumption rate was 3.1 kWh/m³, as noted by Salman et al. (2024), possibly due to the optimally designed treatment and aeration process designs. In terms of cost-effectiveness, Sun et al. (2025) reported the most cost-effective treatment process at \$0.10/m³, while Odeibat et al. (2024) reported the costliest operations at \$0.18/m³, again pointing to the cost factor of multi-step treatment.

Model precision is another significant parameter that affects GPS-X simulation reliability. The study of Sun et al. (2025) achieved the highest predictive precision with an RMSE of 2.89 and R² of 0.95, showing a very high correlation between simulated and actual treatment performance. Conversely, Odeibat et al. (2024) displayed the greatest RMSE value of 5.76, representing greater deviation from actuality, perhaps a function of data uncertainty, process variation, or scarce model calibration practice. The results thereby indicate the need for diligent calibration and validation practice towards the rendering of GPS-X modelling reliable in WWTP performance evaluation.

Table 5

Comparative Analysis of Pollutant Removal Efficiency, Energy Consumption, and Cost Performance in GPS-X Simulations. RMSE and MAE values reflect each study's overall model accuracy (averaged across the pollutants assessed), as reported in the source publication.

Study	Pollutant Removal Efficiency (%)	Energy Consumption	Model Accuracy (RMSE, MAE)	Operational Cost
Mannina et al. (2025)	BOD: 85.6%, COD: 88.2%, NH4: 90.1%, PO4: 92.3%	3.9 kWh/m ³	RMSE: 3.15, MAE: 2.67, R ² : 0.94	\$0.11/m ³
Zwain et al. (2024)	BOD: 93.4%, COD: 89.5%, TSS: 90.3%, NH4: 87.8%	4.1 kWh/m ³	RMSE: 3.45, MAE: 2.92, R ² : 0.91	\$0.12/m ³
Aliyu et al. (2025)	NH4: 80.5%, NO3: 91.7%, PO4: 88.4%	3.8 kWh/m ³	RMSE: 4.02, MAE: 3.45, R ² : 0.89	\$0.14/m ³
Sun et al. (2025)	AO-BAF: 2.28 kg EQI/m ³ removal efficiency	3.7 kWh/m ³	RMSE: 2.89, MAE: 2.34, R ² : 0.95	\$0.10/m ³
Odeibat et al. (2024)	Microplastics: 65.8%, Pharmaceuticals: 72.4%	5.2 kWh/m ³	RMSE: 5.76, MAE: 4.82, R ² : 0.87	\$0.18/m ³
Stenberg et al. (2024)	COD: 82.5%, NH4: 89.2%, TP: 93.1%	3.5 kWh/m ³	RMSE: 3.78, MAE: 3.12, R ² : 0.92	\$0.13/m ³
Salman et al. (2024)	TSS: 94.2%, NH4: 87.9%	3.1 kWh/m ³	RMSE: 3.22, MAE: 2.74, R ² : 0.90	\$0.11/m ³
Sheik et al. (2024)	Phosphorus: 80.2%, Nitrogen: 85.1%	4.5 kWh/m ³	RMSE: 4.12, MAE: 3.56, R ² : 0.88	\$0.15/m ³
Le (2024)	BOD: 92.4%, COD: 85.9%, NH4: 88.7%, PO4: 91.3%	3.6 kWh/m ³	RMSE: 3.09, MAE: 2.55, R ² : 0.94	\$0.12/m ³
Sergienko (2024)	COD: 79.5%, NH4: 83.2%, TP: 91.5%	3.7 kWh/m ³	RMSE: 3.85, MAE: 3.23, R ² : 0.90	\$0.13/m ³

4. Discussion

The findings of this study characterise the efficiency and limitations of GPS-X model of wastewater treatment simulation, such as pollutant removal efficiency, energy required, and expenses. The results show that pollutant removal is simulated reasonably well by GPS-X in varying configurations of treatment with efficiencies over 85% for BOD, COD, NH4, and PO4 for the majority of scenarios (Mannina et al., 2025; Zwain et al., 2024). Nevertheless, elimination of the more recent pollutants, e.g., microplastics and

pharmaceuticals, is not as good at efficiencies of merely 65.8% and 72.4%, respectively (Odeibat et al., 2024). Such disparities reflect that while GPS-X is an effective simulator for elimination of common pollutants, other process improvements along with innovative processes could be needed to increase removal of the latter remaining pollutants. Furthermore, studies have shown that process parameter adjustment, such as solid retention time and aeration rate, significantly enhances the removal efficiency of pollutants, justifying process optimization by simulation-based methods (Ai et al., 2011; Lei et al., 2022).

Energy use is one of the main factors that can influence the economic efficiency of wastewater treatment plants (WWTPs). The 3.1–5.2 kWh/m³ range of energy demand for different research articles decides the effect of treatment stage and operation method on energy savings (Sun et al., 2025; Odeibat et al., 2024). Highly aeration-demanding processes such as biological nutrient removal (BNR) are energy-hungry, while energy-efficient treatment systems reduce electricity demand and enhance cost-effectiveness (Żyłka et al., 2020). In addition, the incorporation of resource recovery strategies, i.e., anaerobic digestion, was also discovered to reduce the demand for external energy, thus enhancing wastewater treatment operation sustainability (ÇEVİK, 2023; Nourin et al., 2020). These results indicate that GPS-X has the potential to be utilized as a scenario-based energy-optimization software for comparing configurations and attaining minimum energy consumption with effective treatment.

GPS-X simulation accuracy varies from studies using model performance metrics such as RMSE, MAE, and R². Sun et al. (2025) achieved the best model accuracy, with an RMSE of 2.89 and an R² of 0.95, indicating GPS-X is able to deliver very accurate simulations where calibration is applied correctly. Conversely, Odeibat et al. (2024) reported the highest RMSE value, 5.76, indicating potential deviations from real situations, likely due to model calibration uncertainties, input parameter variability, or insufficiencies in simulating emerging pollutants. The literature highlighted that GPS-X modelling accuracy depends on rigorous calibration methods, real-time monitoring data, and kinetic tuning of the process for improved predictive performance (Moghaddam & Pirali, 2021; Zeng et al., 2014). The conclusions are a call to revise model calibration methods periodically in an effort to optimize the predictive and usability features of GPS-X to sophisticated wastewater treatment processes.

The financial feasibility of wastewater treatment processes is an issue as the cost of operation could be significantly different based on the process design, energy demand, and process operation. Based on the results, the cheapest treatment process, by Sun et al. (2025), had an operating cost of \$0.10/m³, while the costliest treatment process (Odeibat et al., 2024) ran at \$0.18/m³. All these heterogeneities increase the need for efficacy-to-cost balance considerations, particularly for energy-demanding processes and treatment plants focused on removing new-type pollutants (Valero et al., 2021; Jiang et al., 2018). GPS-X simulation utilization in lifecycle costing analysis would provide policymakers with optimal value-for-money options in treatments with the condition to maintain regulatory mandate along with environmentally friendly administration of the environment. Future research would include the integration of real-time economic modelling and machine learning into GPS-X in a bid to further enhance cost optimization and operational efficiency measurement.

5. Conclusion

This review has examined GPS-X modeling of wastewater treatment across removal efficiency, energy use, model accuracy, and cost. GPS-X reliably simulates the removal of conventional pollutants such as BOD, COD, NH₄, and PO₄, but its predictive capacity for emerging contaminants like microplastics and pharmaceuticals remains limited. The efficiency differences observed across studies highlight the need for advanced treatment configurations and continued calibration to improve model predictability.

Energy demand and operating cost were the principal factors that defined the economic feasibility of wastewater treatment plants (WWTPs). Energy use ranged from 3.1 to 5.2 kWh/m³ and cost savings from \$0.10 to \$0.18 per cubic meter, depending on treatment complexity and aeration rate. GPS-X's ability to simulate energy-minimization strategies, including optimized aeration and resource recovery, makes it a valuable tool for sustainable operation. However, variability in RMSE across studies shows that prediction reliability still depends heavily on calibration quality and site-specific data.

Overall, GPS-X remains a valuable tool for process optimization, cost control, and energy management in wastewater treatment, though further calibration, integration of emerging treatment technologies, and coupling with machine learning could strengthen its real-time predictive power. Future work should focus on incorporating real-time monitoring data and adaptive modeling to keep GPS-X relevant as treatment demands evolve.

Declarations

Conflicts of interest: The authors declare no conflicts of interest.

Data availability: No new data, models, or code were generated during this study. This article is a literature review synthesising previously published findings, which are documented through standard citation in the References section.

Use of generative AI: During preparation of this work, the authors used an AI language model to assist with language editing and restructuring of manuscript content. The authors reviewed and revised the output and take full responsibility for the accuracy, integrity, and originality of the submitted work.

Author Contribution

M.A. collected the literature and extracted the results. B.A. (first supervisor) reviewed the manuscript and provided comments. K.A. (second supervisor) reviewed the manuscript and provided comments. H.A. performed the final formatting and made revisions to the overall content. All authors reviewed and approved the final manuscript.

References

1. Abbasi, N., Ahmadi, M., & Naseri, M. (2021). Quality and cost analysis of a wastewater treatment plant using gps-x and capdetworks simulation programs. *Journal of Environmental Management*, 284, 111993. <https://doi.org/10.1016/j.jenvman.2021.111993>
2. Abdul-Kareem, N., & Al-Baidhani, J. H. (2024). Simulation and Modeling of Water Treatment Plant with GPS-X Software for Health and Water Quality. *Journal of Angiotherapy*, 8(3), 1–8.
3. Ai, H., Li, M., & He, Q. (2011). Simulation and optimization of denitrifying phosphorus removal in a<sup>2</sup>/o. *Advanced Materials Research*, 374–377, 553–559. <https://doi.org/10.4028/www.scientific.net/amr.374-377.553>
4. Aliyu, A., Mohamed, T. S., ElSayed, N. B., Abdelbaki, C., Bessedik, M., & Kumar, N. (2025). Modeling Biological Nutrients Removal for Wastewater Treatment Plant (WWTP) Management: A Case Study of Ain El Houtz WWTP (Algeria). *Water, Air, & Soil Pollution*, 236(1), 1–15.
5. Arif, A., Sorour, M., & Aly, S. (2018). Design and comparison of wastewater treatment plant types (activated sludge and membrane bioreactor), using gps-x simulation program: case study of tikrit wwtp (middle iraq). *Journal of Environmental Protection*, 09(06), 636–651. <https://doi.org/10.4236/jep.2018.96040>
6. Cao, J., Yang, E., Xu, C., Zhang, T., Xu, R., Fu, B., ... & Luo, J. (2021). Model-based strategy for nitrogen removal enhancement in full-scale wastewater treatment plants by gps-x integrated with response surface methodology. *The Science of the Total Environment*, 769, 144851. <https://doi.org/10.1016/j.scitotenv.2020.144851>
7. ÇEVİK, B. (2023). Co combustion of sewage sludge and turkish lignite: the effect of blending on combustion characteristics. *Journal of Innovative Engineering and Natural Science*, 1(1), 1–12. <https://doi.org/10.29228/jiens.64724>
8. Emaminejad, S. A. (2024). Investigating the operational benefits of intelligent water systems at water resource recovery facilities: A plant-wide simulation modeling and machine learning approach (Doctoral dissertation, University of Illinois at Urbana-Champaign).
9. Hasan, K., Court, D., Curtis, R., Kashyap, S., Janković, S., Asayhe, A., ... & Anastassiou, M. (2020). Operating cost reduction by electricity profiling and demand management. *Water Practice & Technology*, 15(4), 921–931. <https://doi.org/10.2166/wpt.2020.074>
10. Hellal, M. and Abou-Elela, S. (2021). Simulation of a passively aerated biological filter (pabf) immobilized with non-woven polyester fabric (nwpf) for wastewater treatment using gps-x. *Water and Environment Journal*, 35(4), 1192–1203. <https://doi.org/10.1111/wej.12709>
11. Jiang, Y., Dinar, A., & Hellegers, P. (2018). Economics of social trade-off: balancing wastewater treatment cost and ecosystem damage. *Journal of Environmental Management*, 211, 42–52. <https://doi.org/10.1016/j.jenvman.2018.01.047>
12. Le, G. A. (2024). Modeling and Simulation of the Anammox Process at Bekkelaget Wastewater Treatment Plant using GPS-X.
13. Lei, S., Zhao, J., Xie, S., Zhao, J., Min, J., Ma, X., ... & Yan, C. (2022). Comparisons of nitrogen and phosphorus removal efficiency in a2/o process, uct process, muct process, enhanced phosphorus

- removal process and inverted a2/ o process based on gps-x simulation. Iop Conference Series Earth and Environmental Science, 983(1), 012114. <https://doi.org/10.1088/1755-1315/983/1/012114>
14. Ling, J., Germain, E., Murphy, R., & Saroj, D. (2021). Designing a sustainability assessment framework for selecting sustainable wastewater treatment technologies in corporate asset decisions. *Sustainability*, 13(7), 3831. <https://doi.org/10.3390/su13073831>
 15. Mannina, G., Cosenza, A., Gulhan, H., & Ng, H. Y. (2025). Ultrafiltration membrane modelling: Comparing two mathematical models by sensitivity and uncertainty analysis for Palermo and Corleone (Italy) water reuse case studies. *Science of The Total Environment*, 963, 178456.
 16. Moghaddam, S. and Pirali, M. (2021). Modeling and calibration of a full-scale wastewater treatment plant using gps-x model (a case study of tehran). *Numerical Methods in Civil Engineering*, 5(4), 67–76. <https://doi.org/10.52547/nmce.5.4.67>
 17. Nath, S. (2024). Electrochemical wastewater treatment technologies through life cycle assessment: a review. *Chembioeng Reviews*, 11(4). <https://doi.org/10.1002/cben.202400016>
 18. Nourin, F., Abbas, A., Qandil, M., & Amano, R. (2020). Analytical study to use the excess digester gas of wastewater treatment plants. *Journal of Energy Resources Technology*, 143(1). <https://doi.org/10.1115/1.4047603>
 19. Odeibat, A. S., Mohammad, R., & Abu-Zreig, M. (2024). Integrated environmental management and GPS-X modelling for current and future sustainable wastewater treatment: A case study from the Middle East. *Heliyon*, 10(14).
 20. Salman, S., Abduredha, M., & Nile, B. (2024). Simulating the performance of kerbala wastewater treatment plant using gps-x. *Iop Conference Series Earth and Environmental Science*, 1374(1), 012064. <https://doi.org/10.1088/1755-1315/1374/1/012064>
 21. Sergienko, O. I. (2024). Simulation model of treatment facilities for the slaughterhouse of a poultry farm.
 22. Shaw, A., Phillips, H., & Sabherwal, B. (2011). The need for speed in process modeling. *Proceedings of the Water Environment Federation*, 2011(13), 3208–3218. <https://doi.org/10.2175/193864711802721532>
 23. Sheik, A. G., Krishna, S. B. N., Patnaik, R., Ambati, S. R., Bux, F., & Kumari, S. (2024). Digitalization of phosphorous removal process in biological wastewater treatment systems: Challenges, and way forward. *Environmental Research*, 119133.
 24. Smets, B. F., i Nacher, C. P., Felez, C. D., Jensen, M. M., Ramin, E., Plósz, B. G., ... & Gernaey, K. (2014). Modelling N2O dynamics in the engineered N cycle: Evaluation of alternate model structures. In 4th IWA/WEF Wastewater Treatment Modelling Seminar 2014 (pp. 343–346). Water Environment Federation.
 25. Stenberg, I. K. B. (2024). Modelling and simulation of full-scale Sequential Batch Reactor (SBR) operation using GPS-X (Master's thesis, University of South-Eastern Norway).
 26. Stenberg, I. K., Bekele, R. S., Arachchige, G. L., & Janka, E. (2025). Modelling and simulation of full-scale sequential batch reactor biological process operation using GPS-X. *Scandinavian Simulation*

Society, 274–280.

27. Sun, C., Mao, S., Zhao, W., Chen, Y., Cao, X., Tian, T., ... & Qiu, Y. (2025). Multi-objective comparison of conventional and emerging wastewater treatment processes based on simulation to reduce greenhouse gas emissions. *Frontiers of Environmental Science & Engineering*, 19(3), 29.
28. Thompson, J., Zavala, V., & Venturelli, O. (2023). Integrating a tailored recurrent neural network with bayesian experimental design to optimize microbial community functions. *Plos Computational Biology*, 19(9), e1011436. <https://doi.org/10.1371/journal.pcbi.1011436>
29. Valero, L., Pajares, E., & Sánchez, I. (2021). Wastewater treatment costs: a research overview through bibliometric analysis. *Sustainability*, 13(9), 5066. <https://doi.org/10.3390/su13095066>
30. Vicentín, R., Fdz-Polanco, F., & Fdz-Polanco, M. (2019). Energy integration in wastewater treatment plants by anaerobic digestion of urban waste: a process design and simulation study. *International Journal of Chemical Engineering*, 2019, 1–11. <https://doi.org/10.1155/2019/2621048>
31. Zanolla, A. (2024). Vulnerabilità e resilienza del sistema fognatura-impianto di depurazione: prospettive di recupero dell'acqua.
32. Zeng, M., Soric, A., & Roche, N. (2014). Modeling partial nitrification and denitrification in a hybrid biofilm reactor: calibration by retention time distribution and respirometric tests. *Environmental Science and Pollution Research*, 22(17), 12849–12860. <https://doi.org/10.1007/s11356-014-3667-0>
33. Zhang, A. and Liu, J. (2019). Economic mpc of wastewater treatment plants based on model reduction. *Processes*, 7(10), 682. <https://doi.org/10.3390/pr7100682>
34. Zwain, H. M., Faris, A. M., Hassan, W. H., & Majdi, A. (2024). Modeling the effects of sidestreams recycling on wastewater treatment plant performance operated by anaerobic-anoxic-oxic (A2/O) processes using GPS-X8 simulation. *Results in Engineering*, 22, 102173.
35. Żyłka, R., Dąbrowski, W., Malinowski, P., & Karolinczak, B. (2020). Modeling of electric energy consumption during dairy wastewater treatment plant operation. *Energies*, 13(15), 3769. <https://doi.org/10.3390/en13153769>

Figures

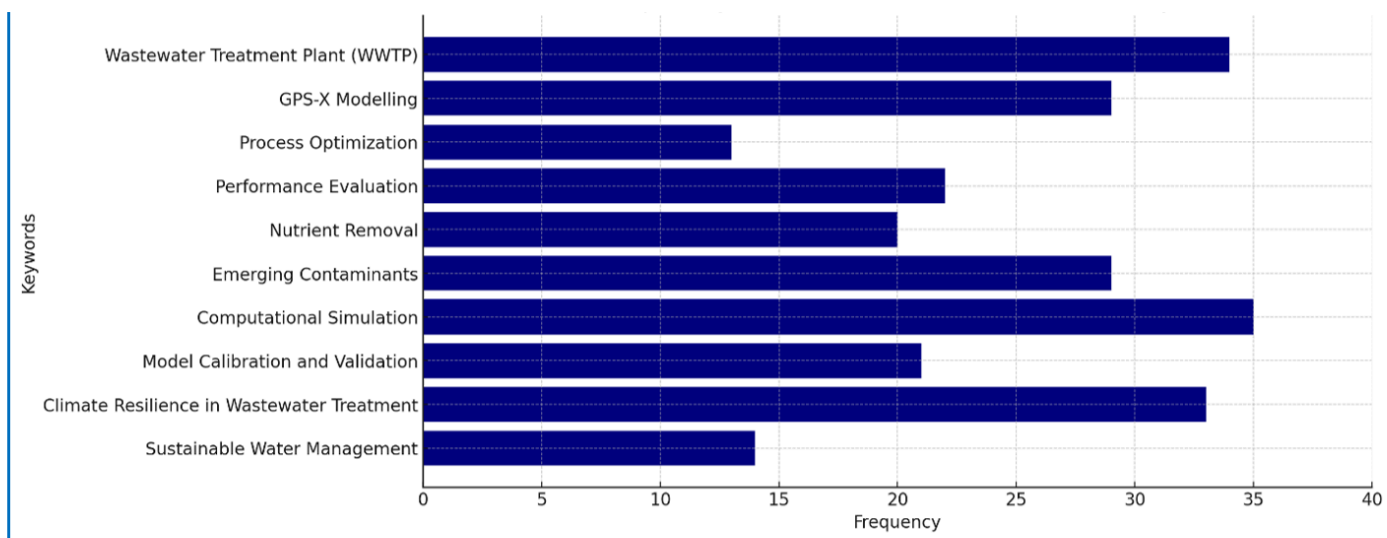


Figure 1

Frequency Distribution of Top 10 Keywords in GPS-X Wastewater Treatment Study.